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RESEARCH MEMORANDUM

PRELIMINARY RESULTS OF TURBOJET-ENGINE ALTITUDE-STARTING INVESTIGATION

By H. D. Wilsted and J. C. Armstrong

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RESEARCH MEMORANDUM

PRELIMINARY RESULTS OF TURBOJET-ENGINE ALTITUDE-STARTING INVESTIGATION

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SUMMARY

The altitude-ignition and altitude-flame-propagation limits of a turbojet engine over a range of simulated flight conditions in an altitude chamber are being investigated at the NACA Lewis laboratory. Preliminary results showed that an energy output at the spark gap of 2.13 joules per spark at a spark-repetition rate of 1 spark per second allowed ignition to 50,000 feet at a flight Mach number of 0.6 with fuel and engine-inlet-air temperature at standard NACA free-stream total temperature. The minimum power required for ignition occurred at low spark-repetition rates (on the order of 1 spark/sec) accompanied by relatively high spark energies.

When the standard engine ignition system was used with 1-pound-per-square-inch Reid vapor-pressure fuel at a simulated flight Mach number of 0.6, a reduction in either fuel or inlet-air temperatures progressively reduced the altitude-ignition limit. A reduction in fuel temperature from 30° to -2° F generally lowered the altitude-ignition limit less than 5000 feet but when the fuel temperature was reduced to -30° F a very abrupt lowering of the altitude limit was found when the air temperature was lower than 0° F. At sea-level conditions, however, ignition with the standard ignition system was obtained to the limit of the refrigerated air systems, -50° F. The effects of spark-gap location and fuel volatility were also investigated.

INTRODUCTION

Engine starts are required at high altitude when combustion blowout is encountered, such as might occur during intercepting or fighting maneuvers. Engine starts are also required at high altitude when a multiengine airplane has been cruising with some of its engines inoperative and requires the remaining engines for evasive action or to increase flight speed. It is important that engine starts be reliably accomplished at altitudes corresponding to the maximum ceiling of the engine or airplane. Otherwise, airplane effectiveness is lost if the engine must be taken to low altitudes for restarting. Starting of a

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turbojet engine requires (1) that ignition in the combustors containing spark plugs or other ignition devices be accomplished, (2) that flame propagation from the combustors with spark plugs to the combustors without spark plugs be accomplished through the cross-fire tubes, and (3) that the engine be accelerated from starting speed to full engine speed without encountering combustion blow-out or compressor stall or surge and without exceeding the allowable temperatures of the engine parts.

A comprehensive study of the turbojet-engine-starting problem is being conducted at the NACA Lewis laboratory to provide criteria for design of reliable starting systems. The purpose of this report is to present some of the preliminary ignition and flame propagation results currently available from this investigation. The altitude-starting investigation is being conducted over a range of simulated flight conditions in an altitude chamber using an axial-flow turbojet engine having a number of individual direct-flow-type combustors. Data are presented to show some of the effects of flight Mach number, spark-gap immersion, fuel volatility, fuel and air temperature, spark-repetition rate, and spark energy on altitude-ignition limits of a production-type turbojet engine. Effect of fuel volatility on flame-propagation limits is also presented.

APPARATUS AND PROCEDURE

The investigation is being conducted in an altitude chamber 10 feet in diameter and 60 feet long. Two axial-flow-compressor-type turbojet engines differing only in the construction of the first stage of the compressor are being used. These engines have a nominal thrust rating of 5000 pounds. For identification, the engines will be designated A and B so that data from the same engine may be compared directly.

The data recorded for this investigation were engine-inlet pressure and temperature, combustor static pressure, extent of flame propagation from combustor to combustor, tail-pipe temperatures, and altitude pressure settings. The extent of flame propagation from one combustor to another was indicated by a temperature rise in the combustors ignited; the temperature rise was detected by thermocouples in the combustor outlets. Altitude pressure settings were measured by use of a static-pressure probe located near the jet-nozzle outlet in the exhaust section of the altitude chamber. The engine-inlet pressures and temperatures were set at standard NACA free-stream total conditions except that the minimum temperature obtainable at the engine inlet under altitude conditions was about -40° F. At the higher air flows required by the engine at sea-level pressures, however, temperatures as low as -50° F were obtained for the simulated cold-weather-starting investigation.

Because preliminary studies showed that the ignition characteristics of the axial-flow engine were more sensitive to engine windmilling speed than to small variations in static pressure, the exhaust pressure was adjusted to obtain the engine windmilling speed determined by a previous calibration for each flight condition investigated.

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The engines were equipped with induction-type ignition systems which discharged about 800 sparks per second at 0.02 joule per spark through AC F-67 spark plugs. This system is shown schematically in figure 1(a). A second ignition system, which was a capacitance-type system as shown schematically in figure 1(b), was added to engine B to allow variation of spark energy, voltage, and sparks per second. For this investigation the voltage indicated by the peak voltmeter was held constant at 10,000 volts. This system discharged into special opposed spark plugs which consisted of 3/16-inch diameter Inconel rods with the tips machined to form a uniform spark gap of 0.11 inch when installed. These heavy electrodes were used to minimize the erosive effects of the high-energy sparks.

The spark energy was determined initially from the known capacitance of the condensers and the voltage to which they were charged as indicated by the peak voltmeter shown in the circuit diagram (fig. 1(b)). A later examination revealed serious losses in the system between the point of measurement and the spark gap and indicated the need for an energy measurement at the spark gap. An attempt was made to measure the heat output of the spark at the spark gap by a comparison method using the apparatus shown in figure 2. The resistance change of the wire grid subjected to the heat released by a fixed number of sparks was compared with a calibration of resistance change versus heater-coil power consumption. A determination was thus made of the equivalent power output for a fixed number of sparks and consequently the energy output per spark. All measurements of spark energy of the variable-energy ignition system were made by the comparison method at approximately sea-level pressure and temperature.

The fuel system of engine A, which is shown in figure 3(a), included duplex fuel nozzles. Fuel temperatures during approximately the first 15 seconds of an attempted start were near inlet-air temperatures, because the fuel system and filters inside the altitude chamber contained about 3 gallons of fuel that were exposed to engine-inlet air for a period of at least 5 minutes before each attempted engine start. If the start required more than the 15 seconds, the fuel temperature tended to rise. In order to obtain a more accurate control of the fuel temperatures, a fuel cooling system was added for use with engine B as shown schematically in figure 3(b). In an attempt to improve the fuel atomization and to obtain equal fuel flow to each combustor, a set of variable-area fuel nozzles and a fuel distributor were used. When cold fuel was used, however, reproducibility of results was difficult and was attributed to sticking of the moving parts of the nozzle. During the later portion of the investigation, small simplex fuel nozzles (5 gal/hr) were installed to insure a high degree of reproducibility of spray pattern and atomization. Ignition-limit reproducibility was appreciably improved; that is, the results were reproduced within 5000 feet, which is the minimum increment of altitude investigated.

The engine throttle during this investigation was either (1) manually controlled, slowly opened and closed during an attempted start, or (2) fixed, opened to a given position as soon as the ignition was turned on and retained in the fixed position until the attempted start was completed. When the fixed throttle technique was used, several attempts were required to investigate a range of fuel flows. The fuels used in this investigation were MIL-F-5624 fuel having a Reid vapor pressure of 5.8 pounds per square inch, MIL-F-24 fuel having a Reid vapor pressure of 6.2 pounds per square inch, and a fuel having a Reid vapor pressure of 1 pound per square inch. The 1-pound-per-square-inch Reid vapor pressure fuel is equivalent to the MIL-F-5624 fuels with sufficient volatiles removed to reduce the Reid vapor pressure to 1 pound per square inch.

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RESULTS AND DISCUSSION

Altitude Ignition

Because engines A and B are nearly alike, only small differences in altitude-starting limits should exist between the two engines and trends with operational and mechanical changes should be the same regardless of which engine is used. The effect of flight Mach number on the altitude-ignition limits of engine B, when the standard-engine-ignition system and a 6.2-pound-per-square-inch Reid vapor pressure fuel are used, is shown in figure 4. Ignition of the combustors containing spark plugs was possible to an altitude of 45,000 feet at a flight Mach number of 0.4. As flight Mach number was increased, the altitude-ignition limit decreased rapidly until at a flight Mach number of 0.8 ignition was not possible at even 5000 feet. This sensitivity to flight Mach number is attributed to the increase in air velocity through the combustors accompanying the rise in windmilling speed as flight Mach number is increased.

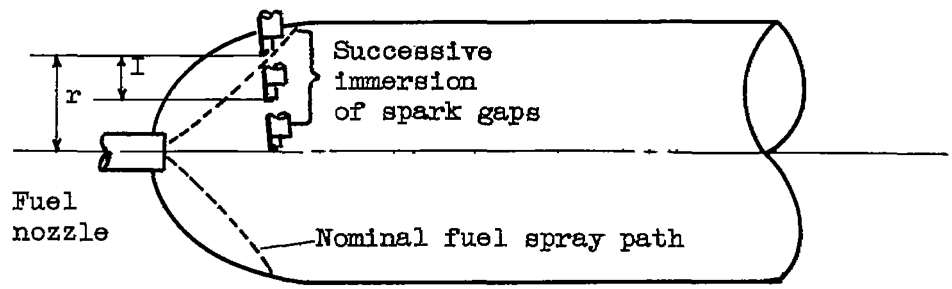
Effect of fuel volatility. - It might be expected when fuel volatility is decreased, with consequent decrease in evaporation rate, that a fuel-air mixture would be more difficult to ignite. The altitude-ignition limit of engine B using the standard-engine-ignition system and a 1-pound-per-square-inch Reid vapor pressure fuel is shown in figure 5 and a comparison of the altitude-ignition limits of the 1- and

6.2-pound-per-square-inch Reid vapor pressure fuels is shown in figure 6. At a flight Mach number of 0.4, the less volatile fuel reduced the altitude-ignition limit by 15,000 feet. At higher flight Mach numbers, this difference was less.

Effect of fuel and air temperatures. - Because the rate of vaporization of fuels decreases with decreasing temperature, a reduction of fuel and air temperatures would be expected to lower altitude-ignition
2214 limits. The effects of fuel and inlet-air temperatures were determined with the 1-pound-per-square-inch Reid vapor pressure fuel in engine B. The investigation was conducted at a simulated flight Mach number of 0.6 except that the exhaust pressures were varied slightly to maintain a constant windmilling speed so as to isolate the temperature effects. The change in altitude-ignition limits obtained by independently varying the fuel and air temperatures is shown in figure 7. A comparison of these altitude limits is shown in figure 8. As either fuel or air temperature was decreased, a progressive decrease occurred in the altitude-ignition limit. A reduction in fuel temperature from 30° to -2° F generally reduced the altitude-ignition limit less than 5000 feet, but when the fuel temperature was reduced to -30° F a very abrupt lowering of the altitude limit was found when the engine-inlet-air temperature was lower than 0° F.

Additional runs were made to determine the minimum fuel and air temperatures at which static sea-level starts could be made with the 1-pound-per-square-inch Reid vapor pressure fuel. Ignition could be obtained at fuel and air temperatures as low as -50° F, the limit of the refrigeration systems for the flows required.

Effect of spark-gap immersion. - Injection of liquid fuel in the form of a hollow cone into the engine combustor results in a very stratified fuel-air mixture. If the electrodes are directly in the liquid fuel stream, ignition is difficult because of the quenching action of the fuel. If the spark electrodes are too far from the fuel spray, the mixture may be too lean for ignition. To explore this effect, spark-gap immersion into the combustor and fuel spray cone angle were varied in engine A using the 5.8-pound-per-square-inch Reid vapor pressure fuel. The largest spray cone angle investigated, 120°, gave the highest altitude limits and data showing the effect of spark-gap immersion on altitude-ignition limits are plotted in figures 9(a) to 9(d). The spark-gap immersion is given as the ratio of the immersion of the spark gap inside the nominal spray cone I to the radius of the spray cone at the spark gap location r. Data are shown for the spark gaps located in the path of the fuel spray ($I/r = 0$) and for progressive immersion until the spark gaps were on the center line of the combustor ($I/r = 1.0$) as shown in the following sketch:



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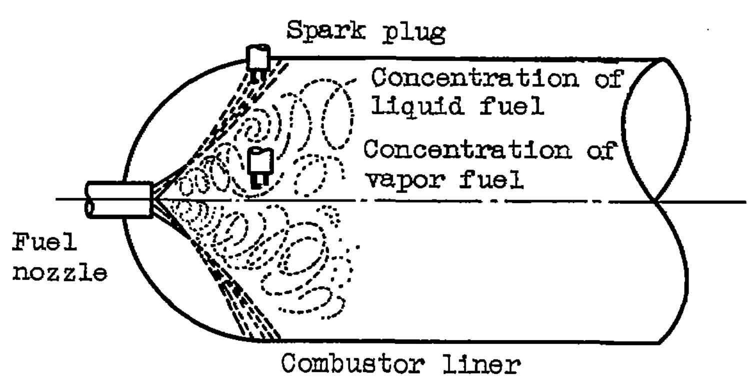
All attempts to start were made by slowly opening and closing the throttle with the ignition on, except for the zero-immersion-ratio data, for which the ignition was turned on and the throttle opened rapidly to establish predetermined fuel flows. Because some of the predetermined fuel flows were too low to obtain ignition, several no-ignition points fall below the ignition limit in figure 9(a). This ignition limit was later spot checked by using the manual- or variable-throttle procedure. A comparison of these data are shown in figure 10. Increasing the spark-gap immersion inside the spray cone generally increased the altitude-ignition limit. The greatest improvement was at the highest flight Mach number (0.85) where the altitude-ignition limit was increased from an altitude of 10,000 to about 35,000 feet.

Similar spark-gap-immersion data were obtained with engine B using the 1-pound-per-square-inch Reid vapor pressure fuel and these results are shown in figure 11. At the low flight Mach numbers the spark-gap immersion had little effect on ignition limits but at the highest flight Mach number (0.8) the altitude limit was increased from sea level to 20,000 feet.

These data may indicate a greater accumulation of fuel vapor near the center of the fuel spray cone and possibly less effect of quenching by the liquid fuel as shown in the following idealized sketch:



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Effect of spark energy. - The effect of spark energy and spark-repetition rate on altitude-ignition limits has been investigated by using the variable-energy ignition system in engine B. This investigation was conducted at a flight Mach number of 0.6 using a 1-pound-per-square-inch Reid vapor pressure fuel. The low-vapor-pressure fuel and relatively high flight Mach number are both detrimental to ignition and under these conditions ignition was possible with the standard ignition system to an altitude of only 15,000 feet. The relation of spark energy to spark-repetition rate required to obtain ignition at an altitude of 50,000 feet is shown in figure 12. At an input of 0.34 joule per spark, 184 sparks per second were required for ignition, but at an input of 1.05 joules per spark only 15 sparks per second were required for ignition. At the next higher spark energy available from the ignition system, 2.13 joules per spark, only 1 spark per second was required for ignition. From an extrapolation of the curve it is evident, however, that ignition could have been obtained at 1 spark per second at a spark energy of approximately 1.3 joules per spark.

These data show that there is a wide range of spark energy and spark-repetition rate that will produce ignition at an altitude of 50,000 feet in the engine used. The data are therefore replotted in figure 13 to show the power (joules/spark)(sparks/sec) required for ignition. The minimum power requirements of the power source occurred when a high energy per spark and a low spark-repetition rate were used. The minimum power measured was 2.13 joules per second obtained at 2.13 joules per spark and 1 spark per second. However, the extrapolation of figure 12, which is replotted in figure 13, indicates that ignition probably could have been obtained at about 1.3 joules per second. The trend of figure 13 emphasizes that the use of a high spark energy at a low repetition rate can result in a large reduction in power required for ignition as compared with a low spark energy at a high repetition rate.

For 1 spark per second, the spark energy required for ignition with increasing altitude was investigated and the results are shown in figure 14. The measured energy required for ignition at 35,000 feet was 0.24 joule per spark and at 50,000 feet was 2.48 joules per spark. Ignition was not possible at 55,000 feet with the maximum output of the ignition system (3.74 joules/spark) at 1 spark per second. The data of figure 14 show that very large increases in energy are required for ignition above an altitude of 45,000 feet at a flight Mach number of 0.6.

During this investigation a serious operational problem was encountered with the standard aircraft harness connectors which were used in both ignition systems and caused considerable difficulty when operated at high altitude. Corona discharges occurred in the air pockets in the connectors and decomposed the insulating silicone grease to the degree that no spark occurred in the spark gap. These difficulties strongly indicate the need for connectors from which all air pockets can easily be purged.

Flame Propagation

The effect of flight Mach number on the altitudes to which flame propagation could be obtained with three different fuels is shown in figure 15. The data in figure 15(a) show a decrease in the flame-propagation limit as flight Mach number was increased from 0.25 to 0.40. 2214
At flight Mach numbers above 0.40, the effect of flight Mach number on the propagation limit was negligible. A comparison of the altitude-flame-propagation limit for 1- and 6.2-pound-per-square-inch Reid vapor pressure fuels is shown in figure 16. The less volatile fuel reduced the propagation limit about 5000 feet between flight Mach numbers of 0.4 and 0.8.

SUMMARY OF RESULTS

An investigation of altitude ignition and flame propagation in progress at the NACA Lewis laboratory using axial-flow-compressor turbojet engines has produced the following preliminary results:

An energy output at the spark gap of the ignition system of 2.13 joules per spark at a spark-repetition rate of 1 spark per second allowed ignition to 50,000 feet at a flight Mach number of 0.6 with fuel and engine-inlet-air temperatures at standard NACA free-stream total temperature. The minimum power required for ignition was shown to occur at low spark-repetition rates (on the order of 1 spark/sec) accompanied by relatively high spark energies. Altitude-ignition limits decreased rapidly with increasing flight Mach number with the spark gaps in the nominal fuel spray path, but by increasing the spark-gap immersion inside the fuel spray cone the effect of flight Mach number was decreased.

A reduction of fuel volatility from 6.2- to 1-pound-per-square-inch Reid vapor pressure reduced the altitude-ignition limits by as much as 15,000 feet and the altitude-flame-propagation limits by about 5000 feet. When using the standard engine ignition system with a 1-pound-per-square-inch Reid vapor pressure fuel at a simulated flight Mach number of 0.6, a reduction in either fuel or inlet-air temperatures progressively reduced the altitude-ignition limit. A reduction in fuel temperature from 30° to -2° F generally lowered the altitude-ignition limit less than 5000 feet, but when the fuel temperature was reduced to -30° F, a very abrupt lowering of the altitude limit was found when the engine-inlet-air temperature was lower than 0° F. At sea-level static conditions, however, ignition with the standard system was obtained to the limit of the refrigeration systems, -50° F.

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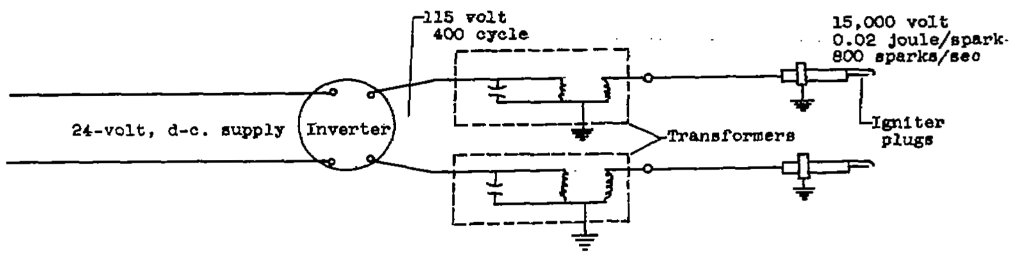
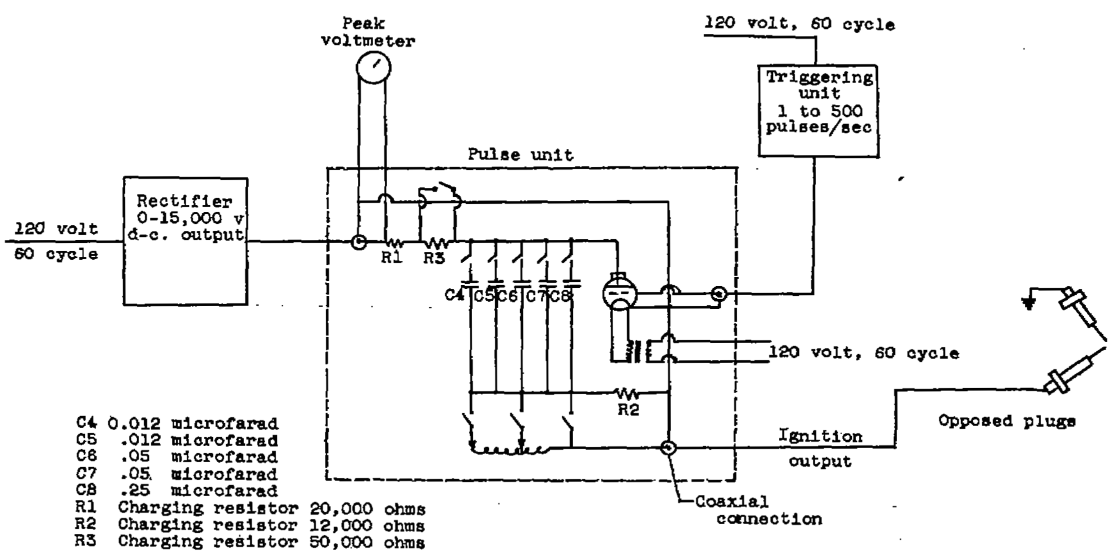
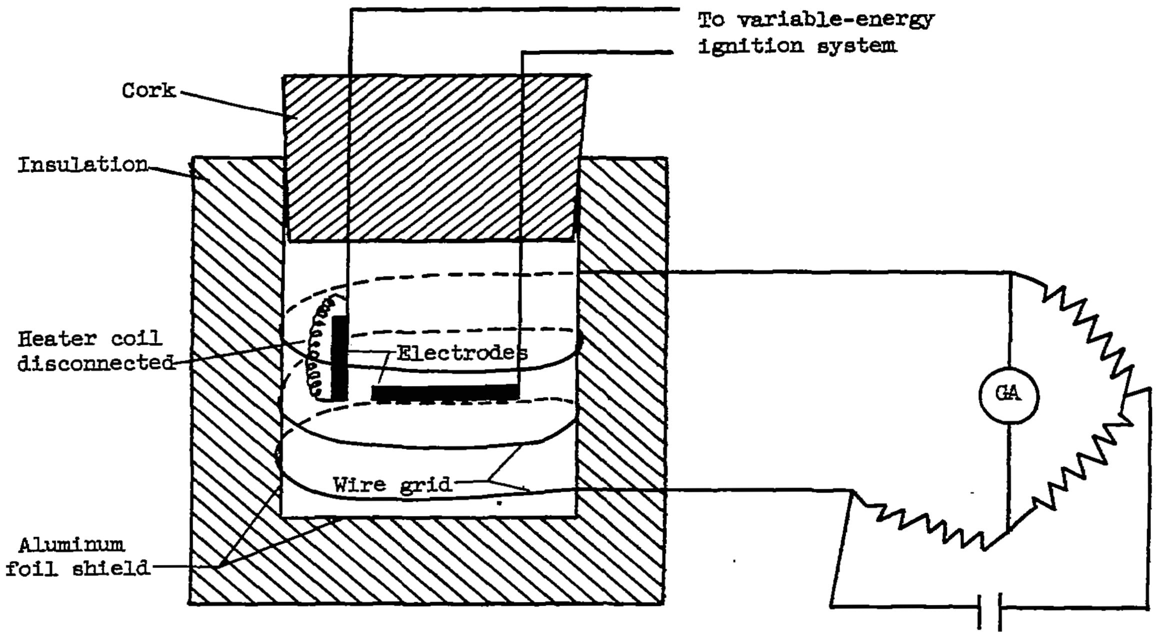


(a) Standard inductance-type ignition system for engines A and B.

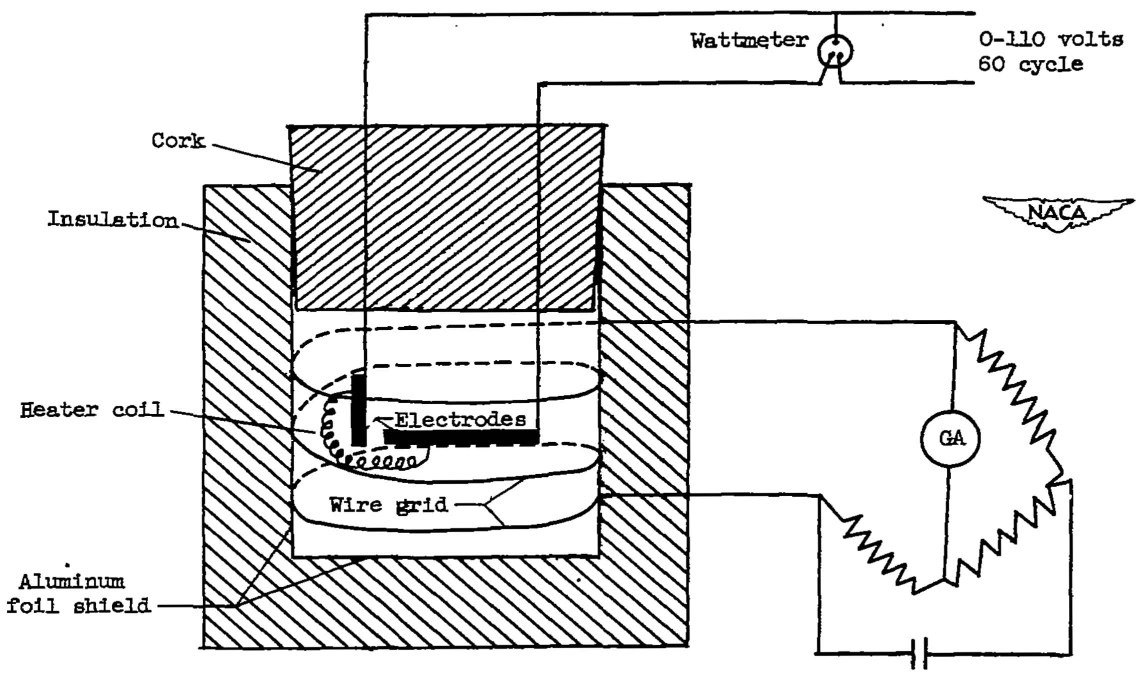


(b) High-energy variable-sparking-rate capacitance-type ignition system for engine B.

Figure 1. - Schematic diagram of ignition systems.



(a) Setup to determine grid-resistance change of various spark outputs.



(b) Setup to calibrate grid-resistance change versus heater-coil power consumption.

Figure 2. - Schematic diagram of system used to determine spark energy.

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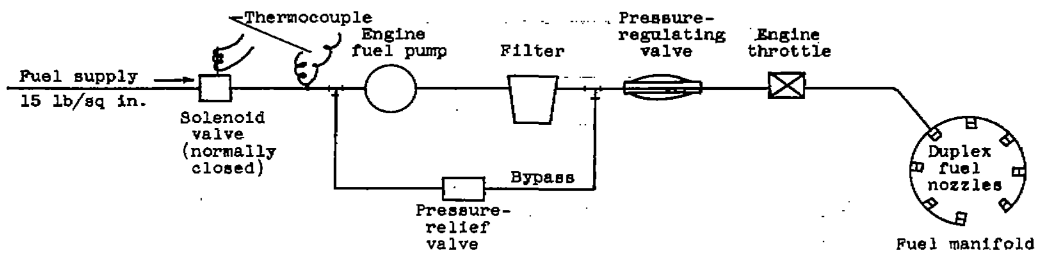
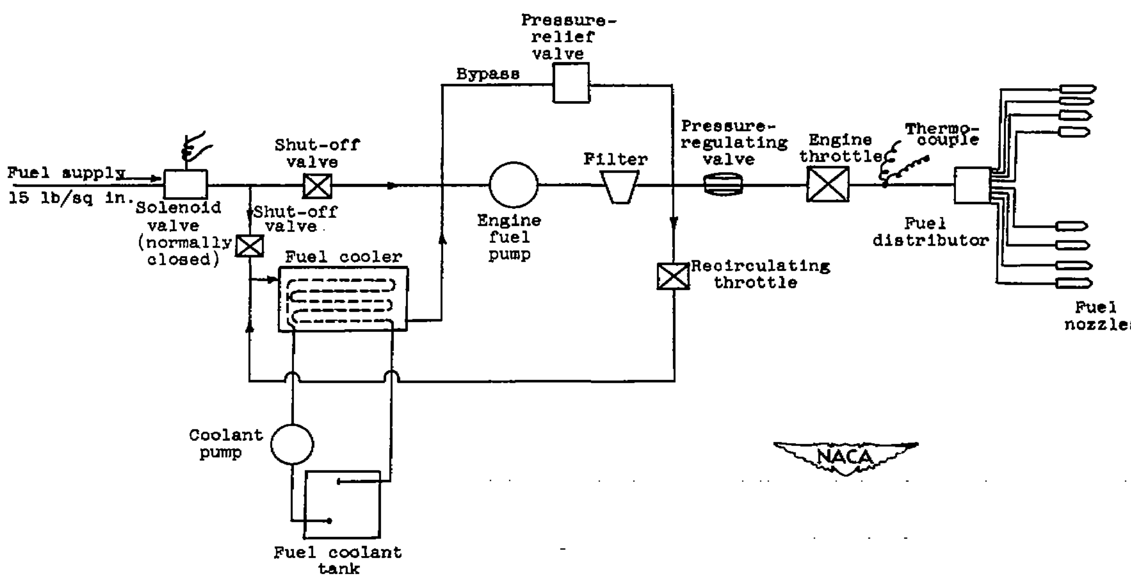


(a) Fuel system used with engine A.



(b) Fuel system used with engine B.

Figure 3. - Schematic diagrams of fuel systems.

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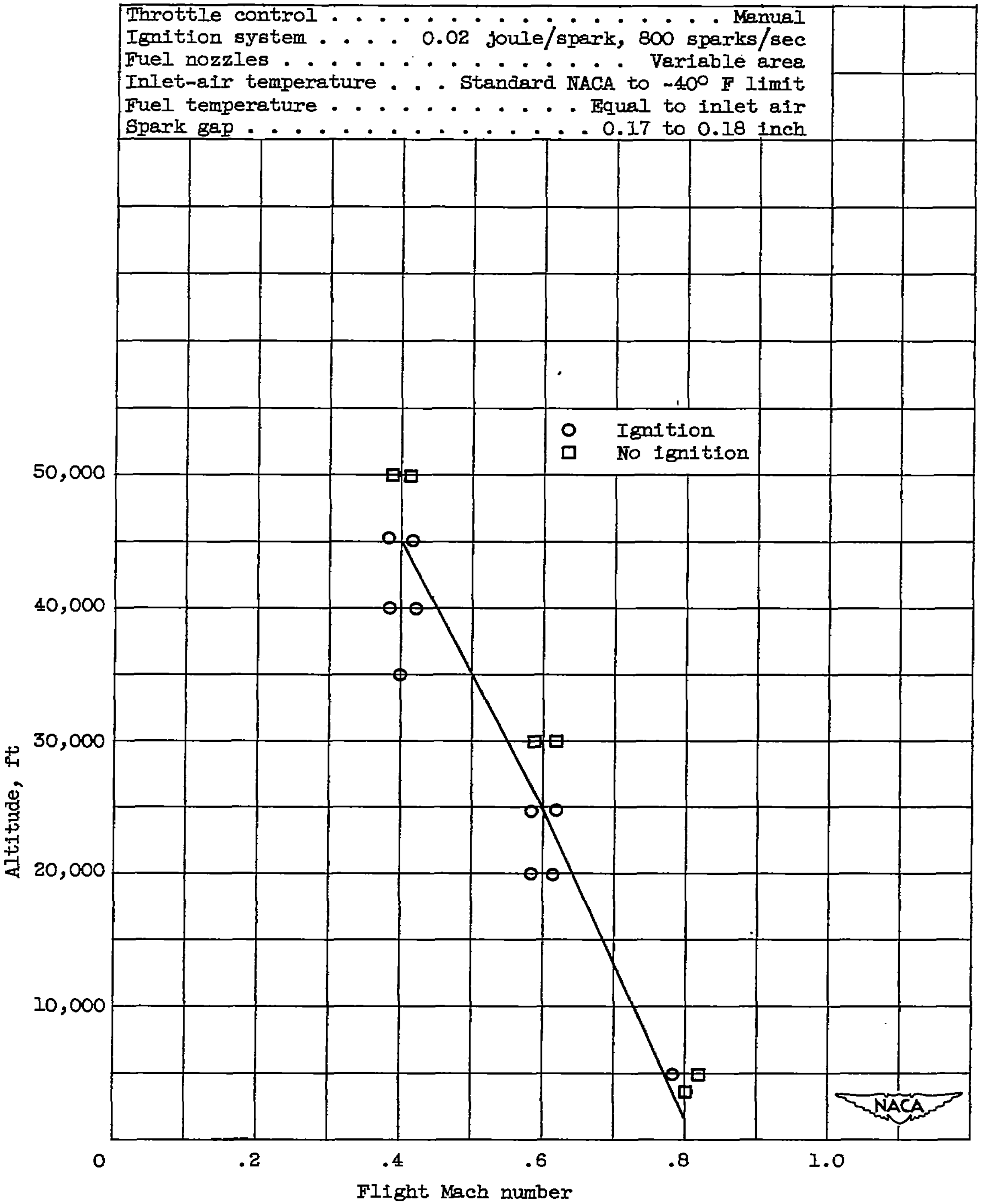

Figure 4. - Altitude-ignition limits of turbojet engine B using 6.2 pound-per-square-inch Reid vapor pressure fuel with standard ignition system.

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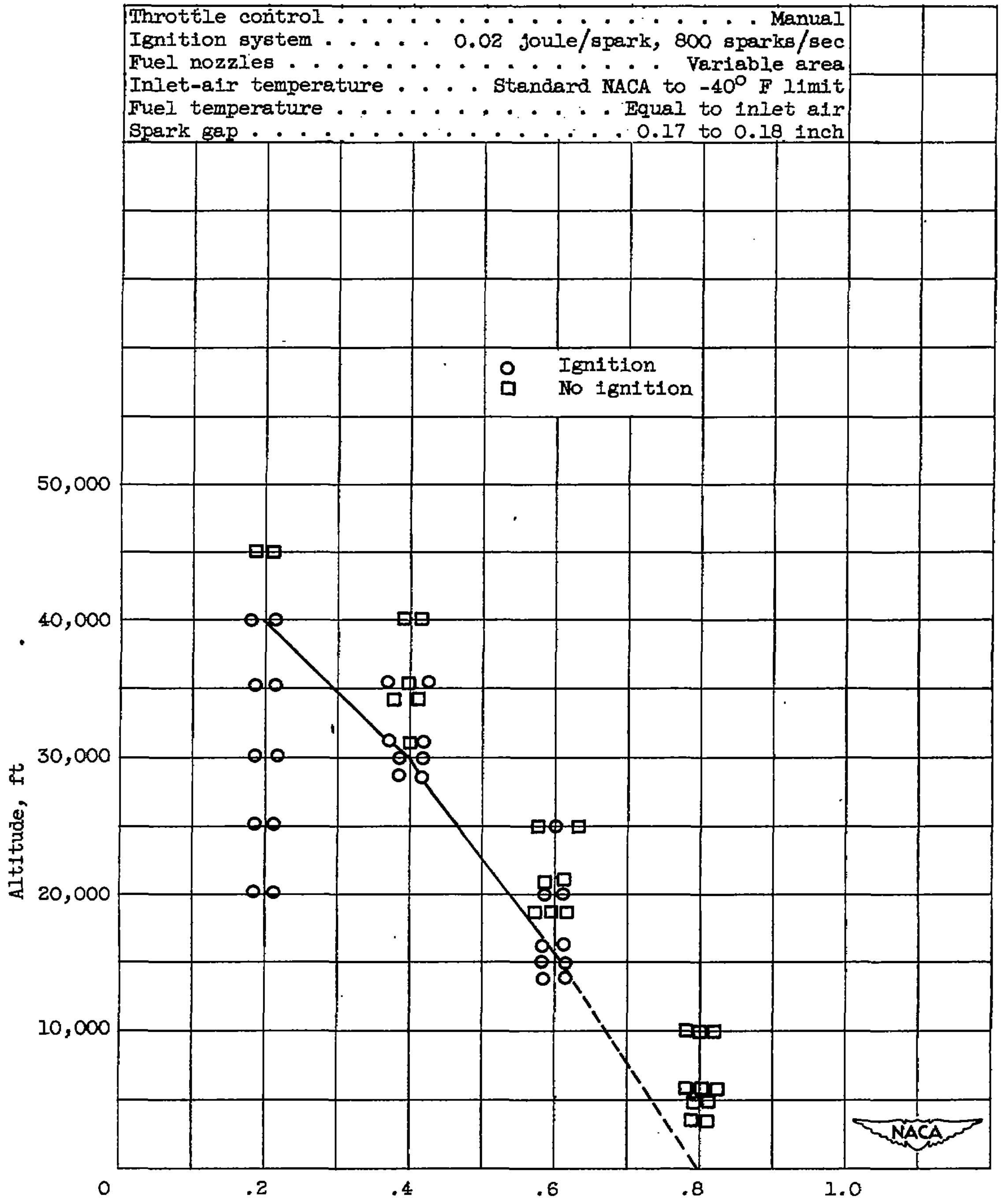

Figure 5. - Altitude-ignition limits of turbojet engine B using 1-pound-per-square-inch Reid vapor pressure fuel with standard ignition system.

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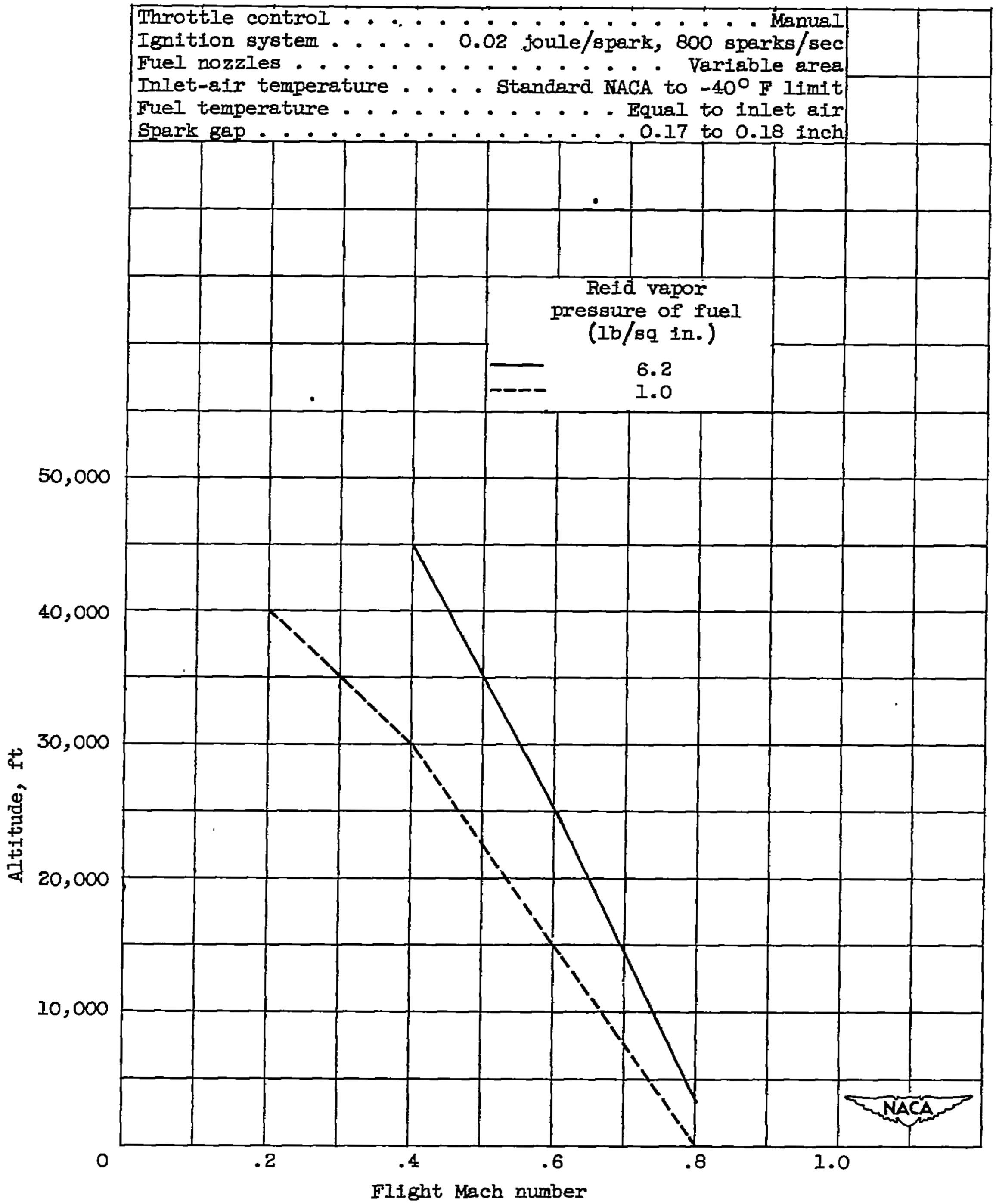
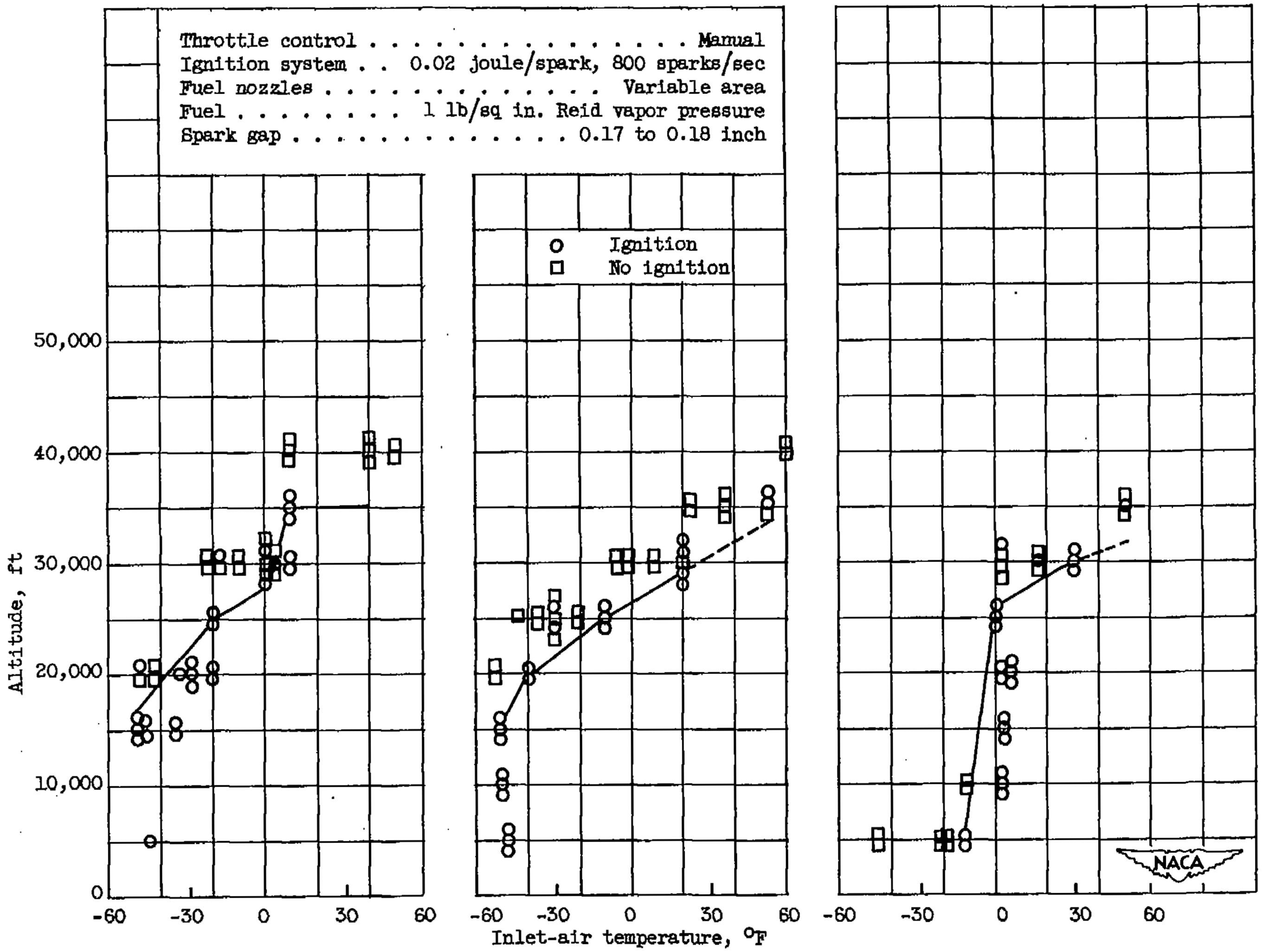


Figure 6. - Effect of fuel volatility on altitude-ignition limits of turbojet engine B with standard ignition system.



(a) Fuel temperature, 30° F.　(b) Fuel temperature, -2° F.　(c) Fuel temperature, -30° F.

Figure 7. - Effect of inlet-air temperature on altitude-ignition limits of turbojet engine B with standard ignition system at various fuel temperatures. Engine windmilling speed, 2020 rpm; and flight Mach number, approximately 0.6.

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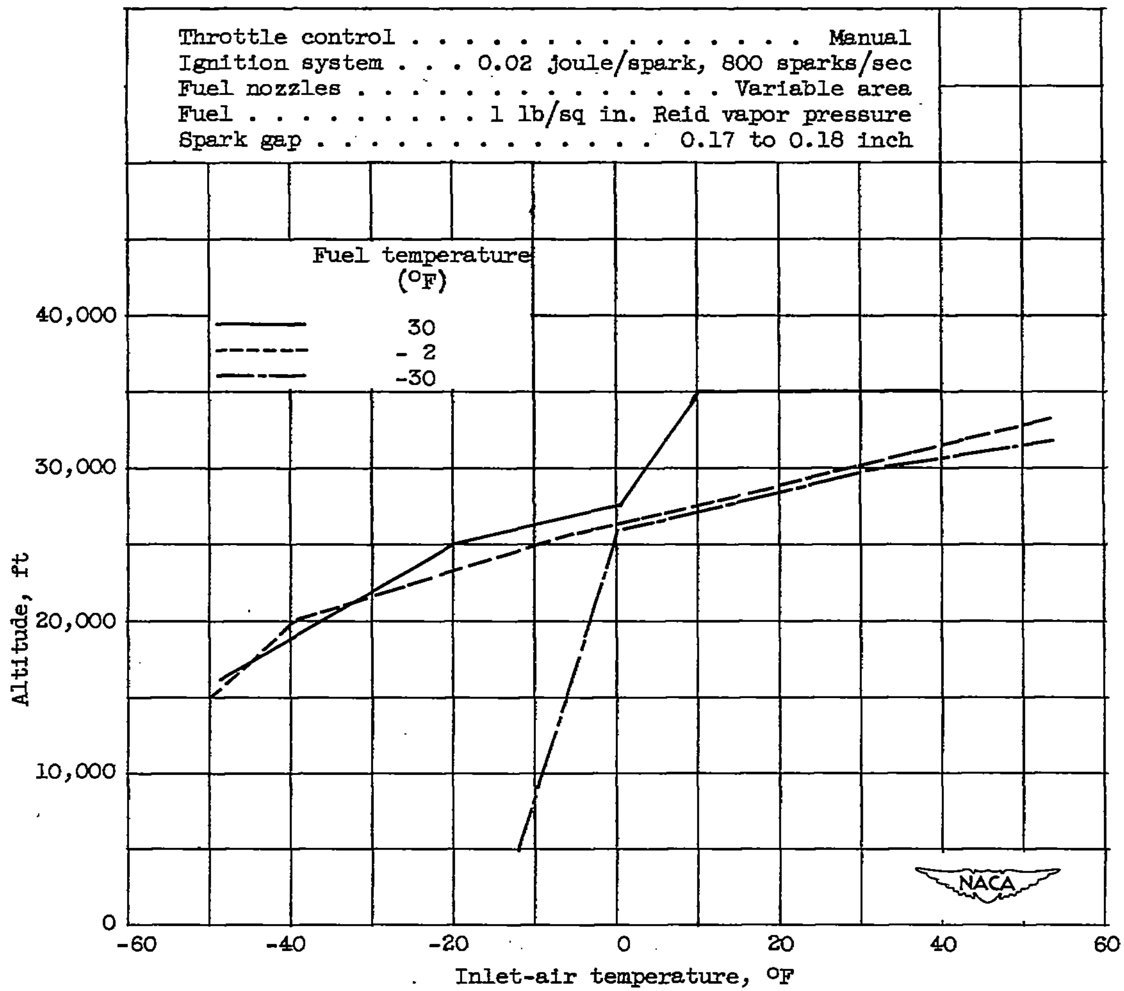

Figure 8. - Effect of fuel and inlet-air temperatures on altitude-ignition limits of turbojet engine B with standard ignition system. Engine windmilling speed, 2020 rpm; and flight Mach number, approximately 0.6.

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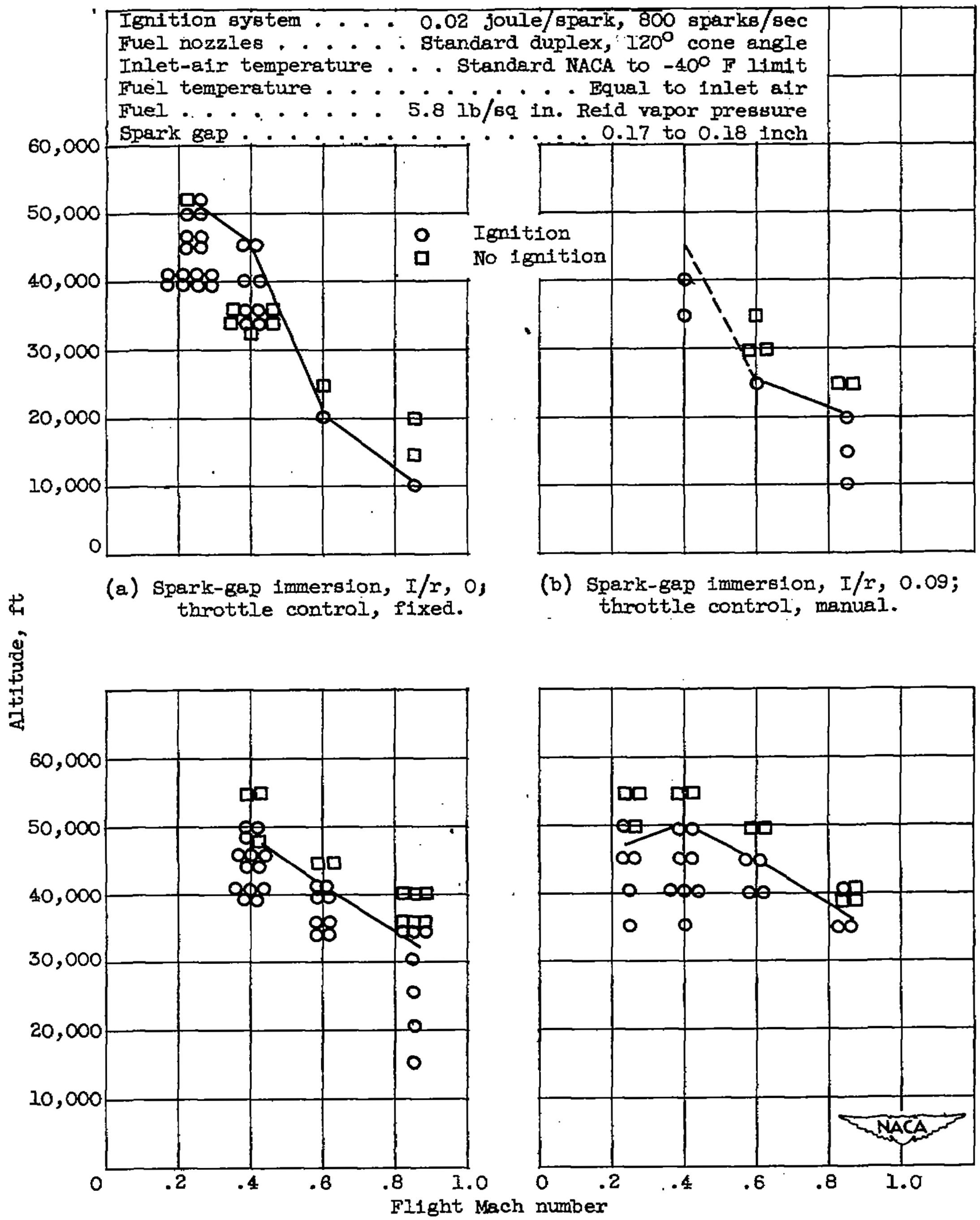

(a) Spark-gap immersion, I/r, 0; throttle control, fixed.

(b) Spark-gap immersion, I/r, 0.09; throttle control, manual.

(c) Spark-gap immersion, I/r, 0.36; throttle control, manual.

(d) Spark-gap immersion, I/r, 1.00; throttle control, manual.

Figure 9. - Altitude-ignition limits at various spark-gap immersions inside spray cone for turbojet engine A with standard ignition system.

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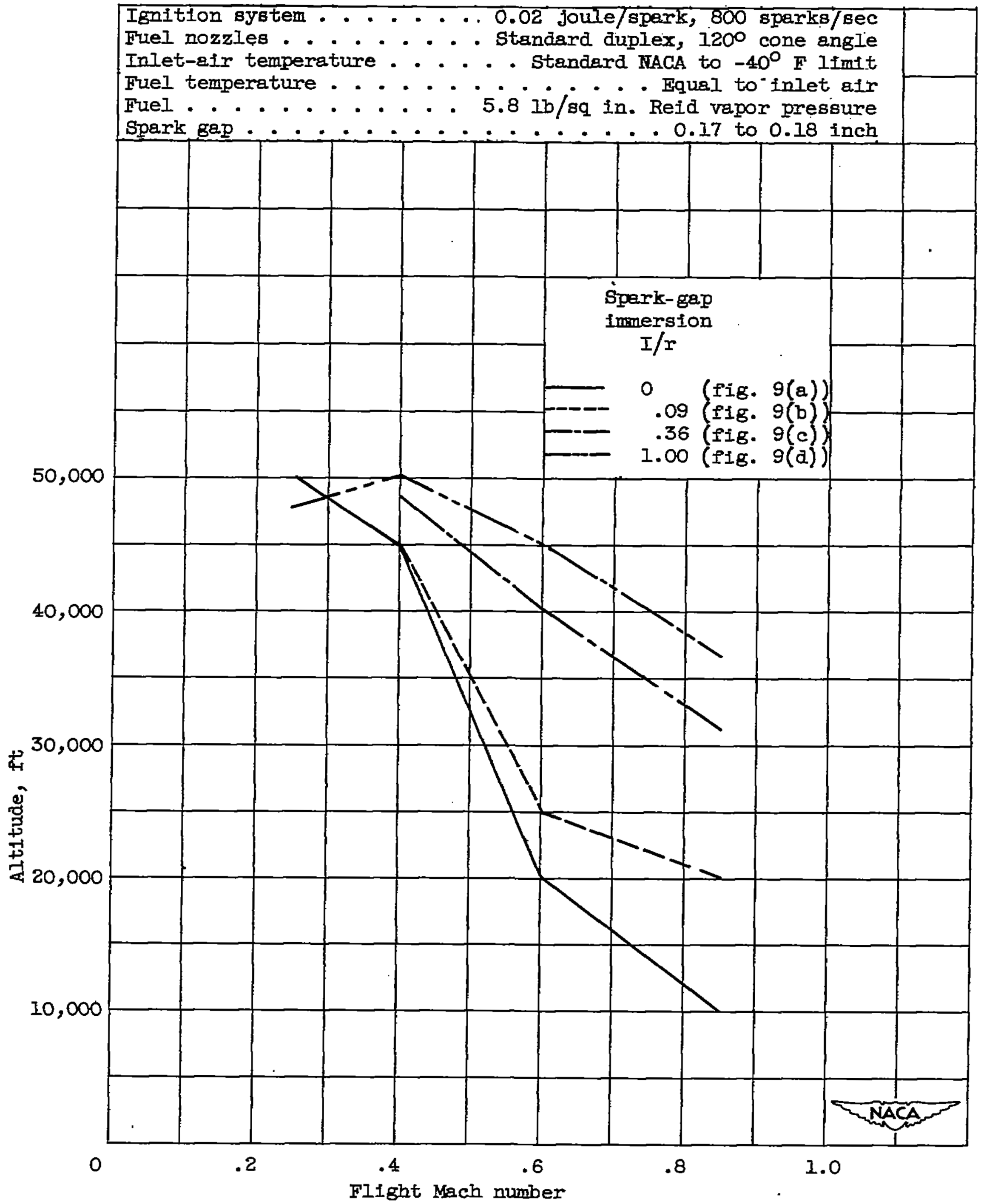

Figure 10. - Effect of spark-gap immersion on altitude-ignition limits of turbojet engine A with standard ignition system.

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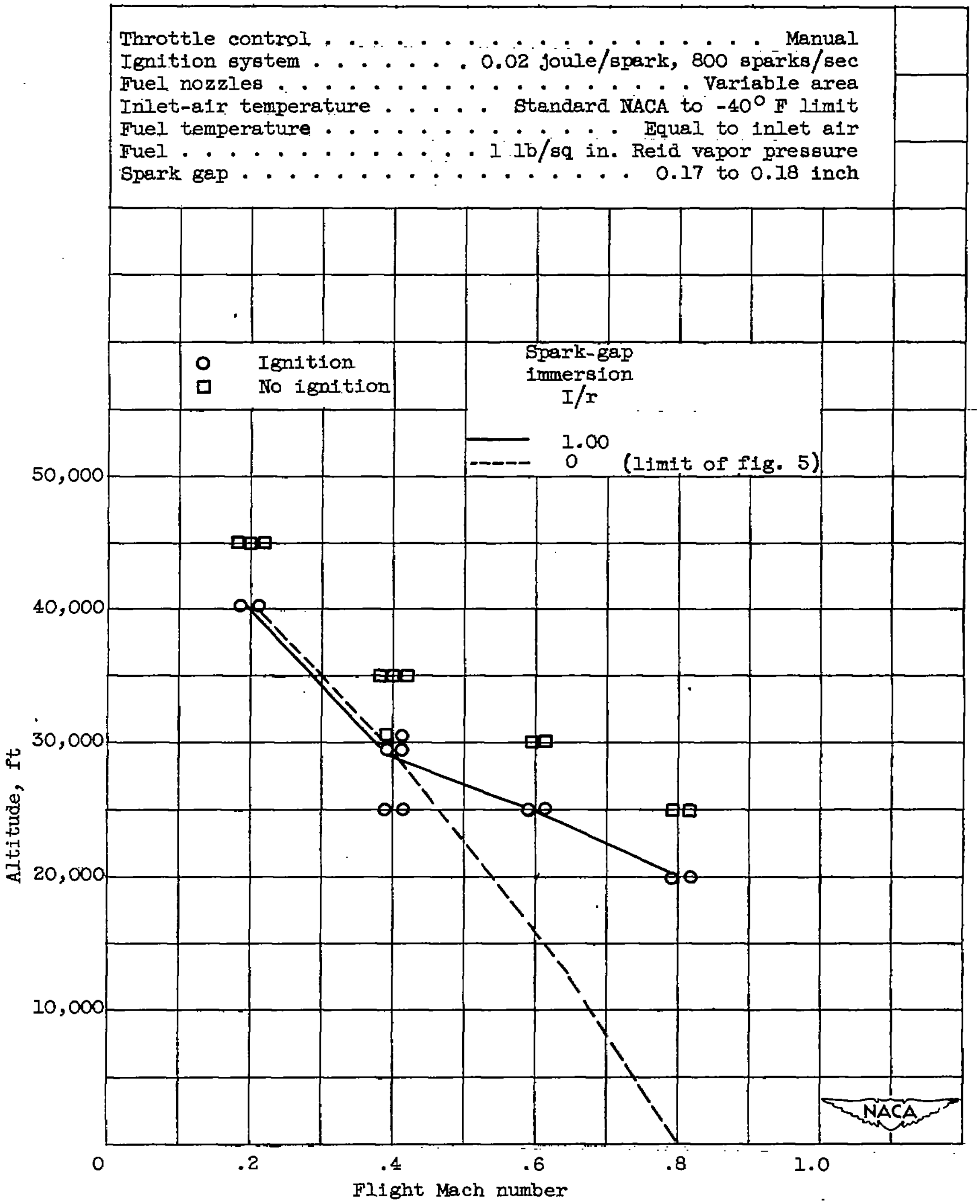

Figure 11. - Effect of spark-gap immersion on altitude-ignition limits of turbojet engine B with standard ignition system.

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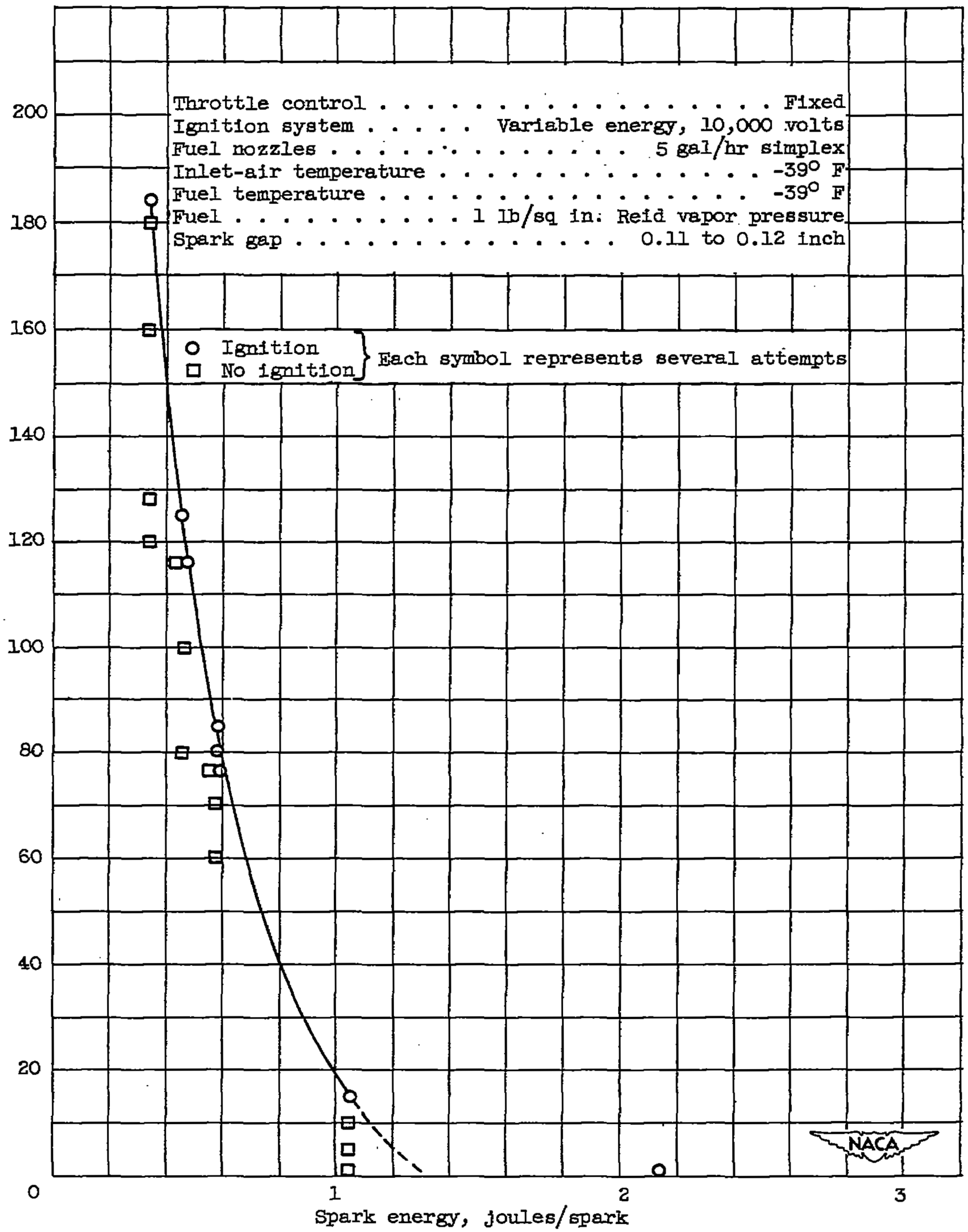

Figure 12. - Spark energy and spark-repetition rate required for ignition at altitude of 50,000 feet and flight Mach number of 0.6 for turbojet engine B.

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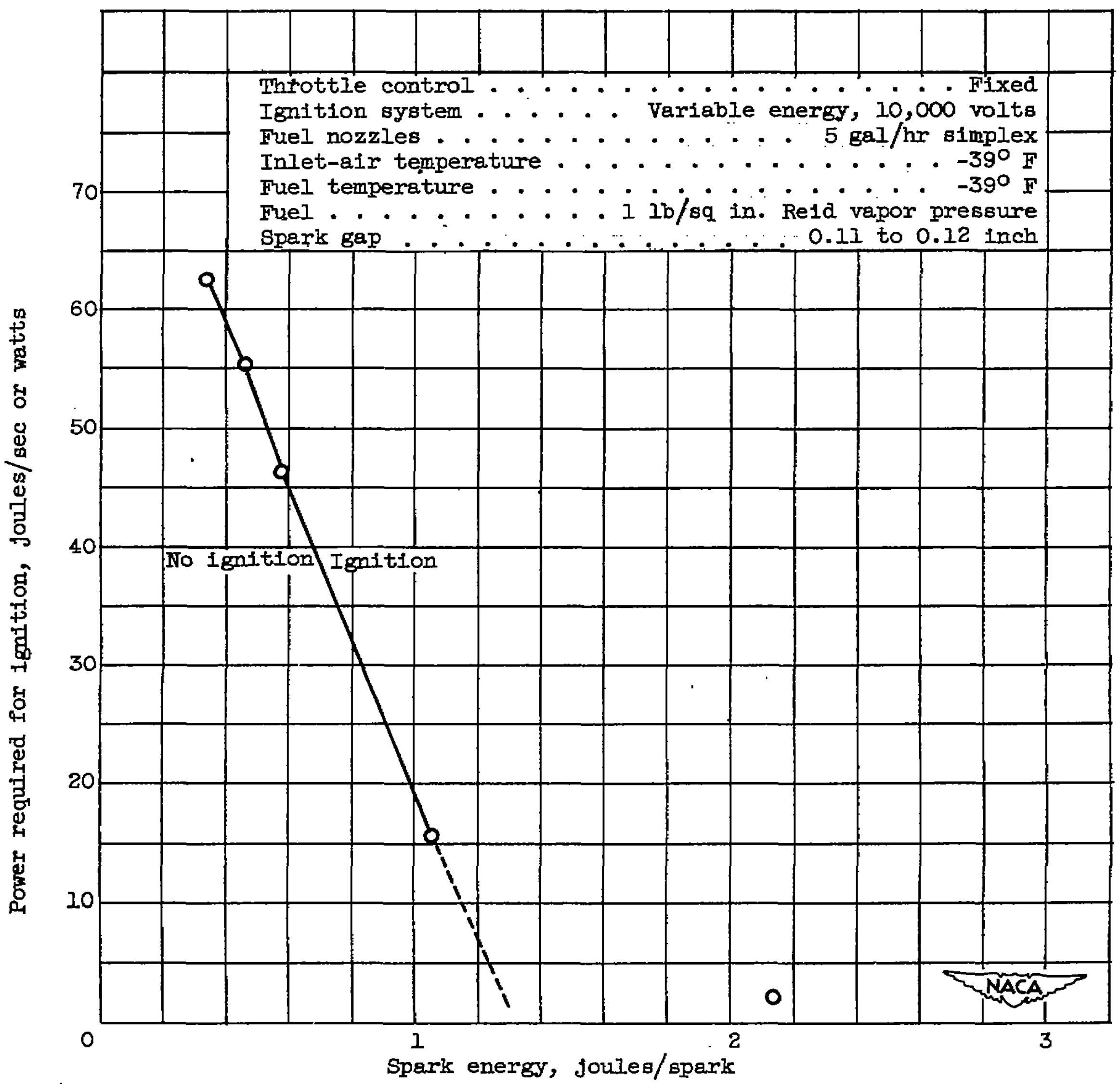

Figure 13. - Power required for ignition at altitude of 50,000 feet and flight Mach number of 0.6 for turbojet engine B.

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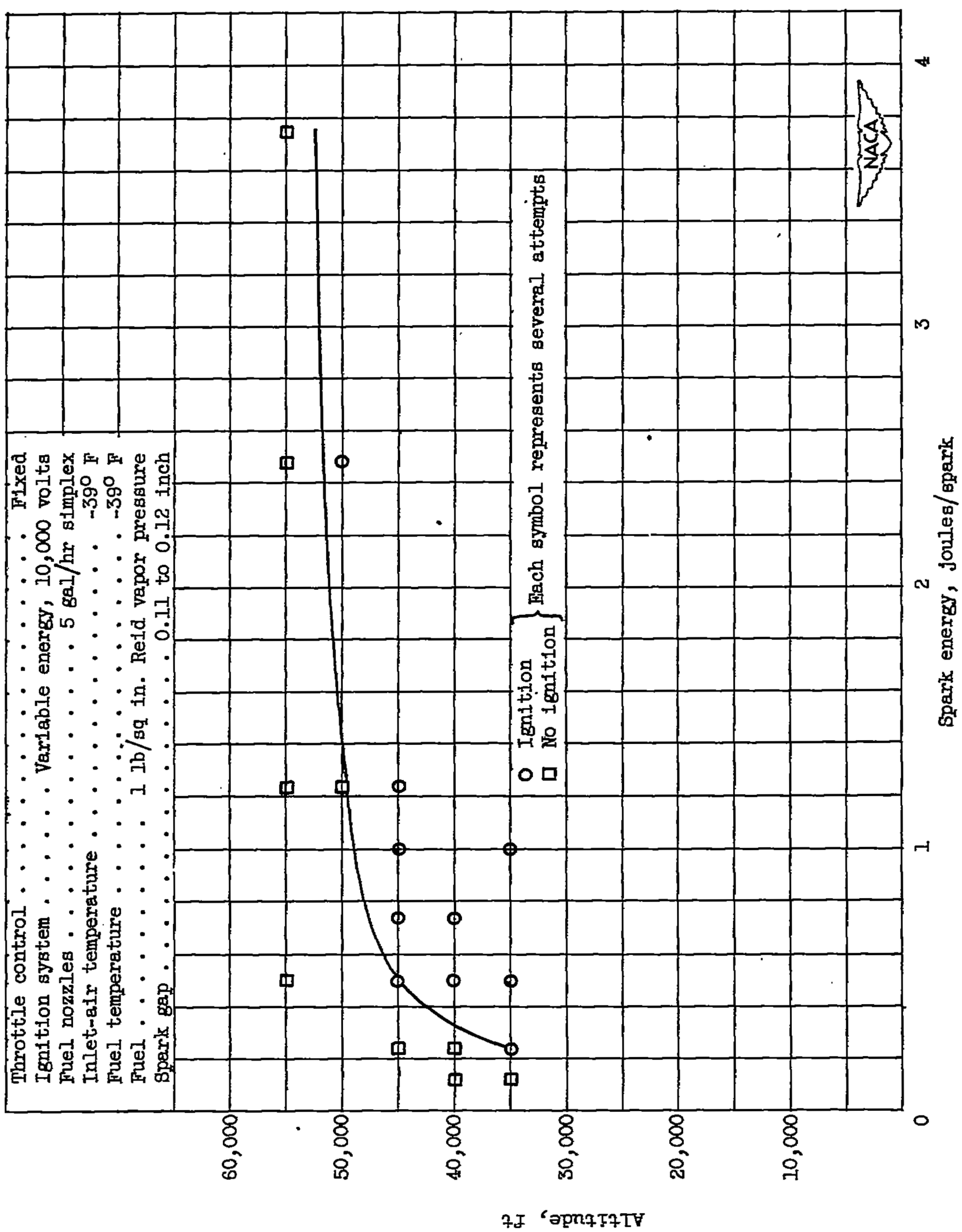

Figure 14. - Energy required for ignition of turbojet engine B with increasing altitude at flight Mach number of 0.6. Spark-repetition rate, 1 spark per second.

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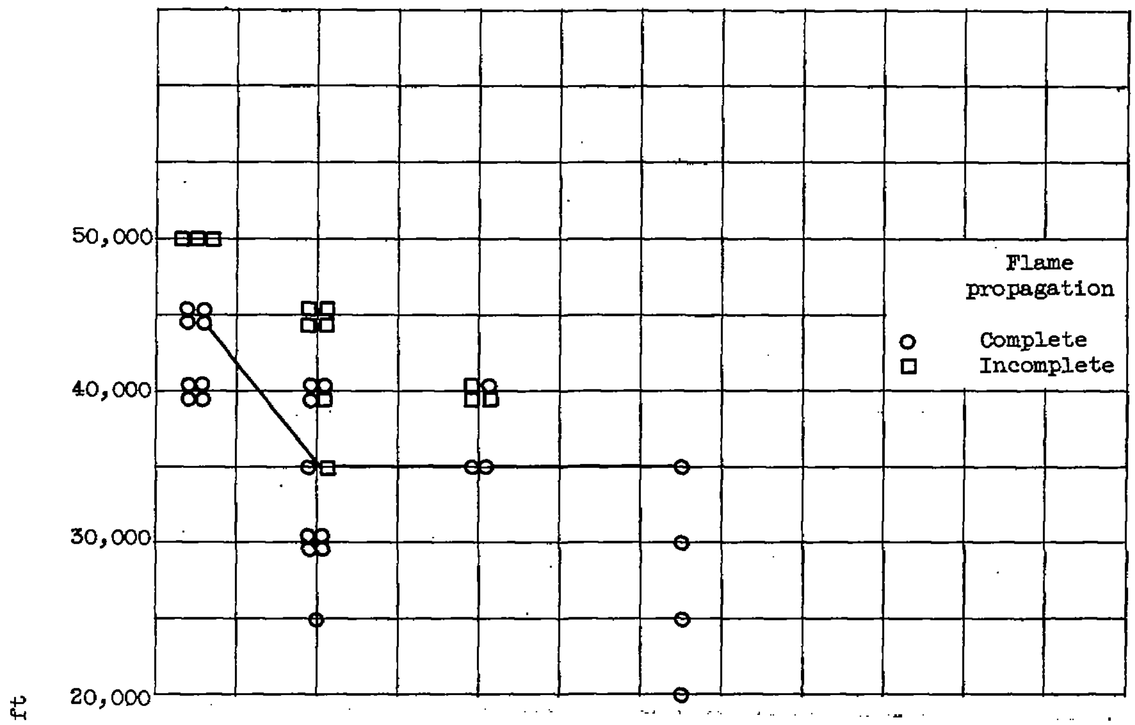
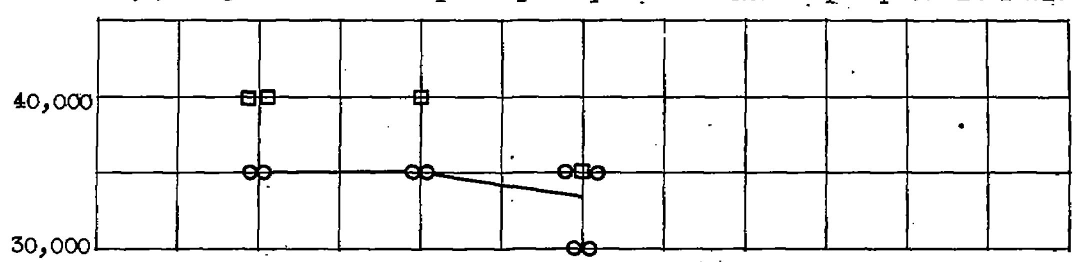
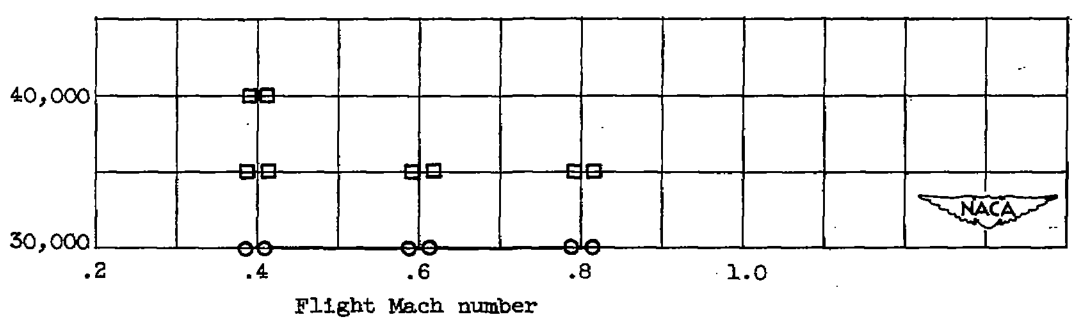


(a) Engine A with 5.8-pound-per-square-inch Reid vapor pressure fuel.



(b) Engine B with 6.2-pound-per-square-inch Reid vapor pressure fuel.



(c) Engine B with 1-pound-per-square-inch Reid vapor pressure fuel.

Figure 15. - Altitude-flame-propagation limits of turbojet engines A and B.

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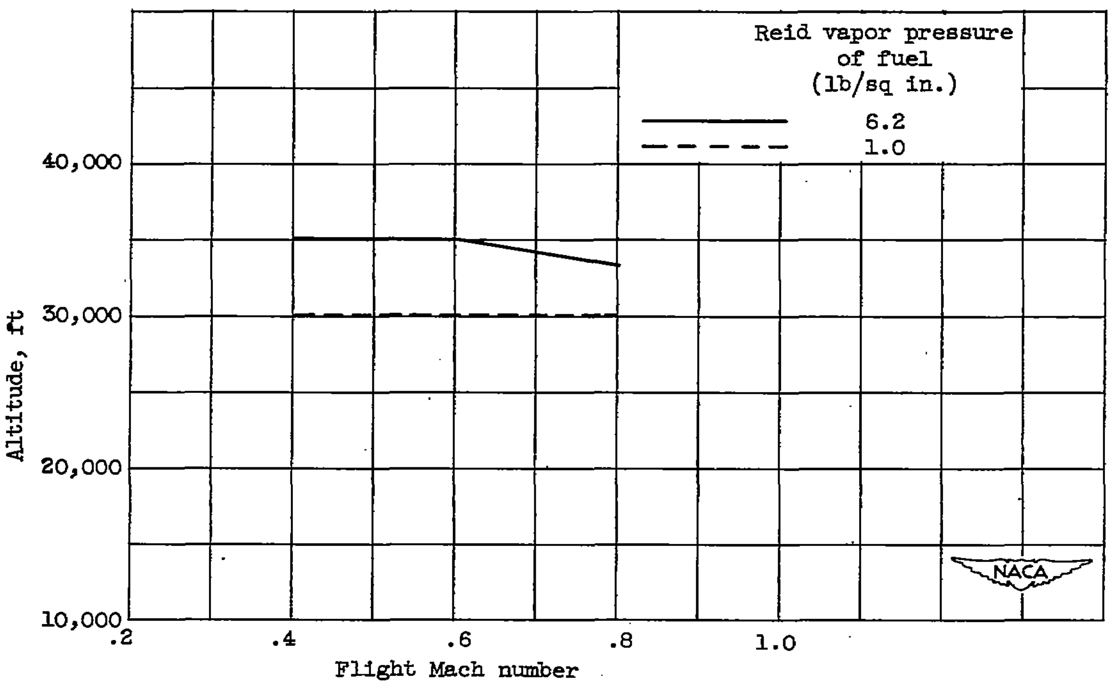

Figure 16. - Effect of fuel volatility on altitude at which flame propagation to all combustors could be obtained with turbojet engine B.

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